

# ***Integrated Fast Neutron Flux At The End Of Phase-IV Part-2 (50 GWd/t) Of The MOX Zr- Cladding Tubes***

*Gray S. Chang*

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*Idaho National Engineering and Environmental Laboratory  
Bechtel BWXT Idaho, LLC*

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**Idaho National Engineering and Environmental Laboratory  
Nuclear & Radiological Sciences Department  
Idaho Falls, Idaho 83415**

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## **ABSTRACT**

This report documents the MCWO-calculated Zr-cladding fast neutron fluence ( $E > 0.1$  MeV and  $E > 1.0$  MeV) distributions at the end of each cycle (127C to 132C) during the irradiation Phase-IV-2 (50 GWd/t) using the detailed ATR quarter core model calculated neutronic tallies. The integrated Zr-cladding fast neutron fluence distributions are tabulated in Tables 1 to 9. At the end of the Phase-IV part-2 irradiation, the MCWO-calculated Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6, and 12 are 1.71, 1.68, and  $1.68 \times 10^{21}$  n/cm<sup>2</sup>, respectively.



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## INTRODUCTION

To support potential licensing of MOX fuel made from WG-plutonium and depleted uranium for use in United States reactors, an experiment containing WG-MOX fuel was fabricated and was irradiated in the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL). The uninstrumented test assembly initially containing nine MOX fuel capsules and neutron monitor wires was inserted into the ATR for irradiation to achieve a burnup of 50 GWd/t. The Oak Ridge National Laboratory (ORNL) manages this project for the Department of Energy.

The Monte Carlo depletion tool (MCWO)<sup>1</sup> used in this study provides an accurate correction factor for the reactor parameters, such as capture-to-fission ratios, isotopic concentrations and compositions, fission power, and fast neutron flux versus burnup.

## WG-MOX FUEL TESTING IN THE ATR

The initial experiment phase (Phase-I irradiation), which contained nine MOX fuel capsules, was loaded into the ATR in January 1998. After 153.5 effective full power days (EFPDs) of irradiation in Phase-I,<sup>2</sup> a capsule pair was withdrawn from the ATR in September 1998 after having achieved an average discharge burnup of about 8.6 GWd/t. At the end of Phase-II<sup>3</sup> irradiation (226.9 EFPDs), an additional capsule pair was withdrawn in September 1999 after having achieved an average discharge burnup of about 21.5 GWd/t. Also, at the end of Phase-III<sup>4</sup> irradiation (232.8 EFPDs), an additional capsule pair was withdrawn in September 2000, after having achieved an average discharge burnup of about 29.6 GWd/t. The Phase-IV part 1A MOX capsule arrangement was achieved by placing Capsules 6 and 12 in the two front top positions, Capsules 4 and 13 in the two front middle positions, and Capsule 5 in the back middle position as shown in Table 4A Capsule ID column. The other four assembly positions were filled with dummy SST capsules. To increase the linear heat generation rate (LHGR) during the Phase-IV part-1B,<sup>5</sup> starting at Cycle 126B, the MOX fuel test assembly was moved to SW I-23 position. At the end of Phase-IV part 1B, the capsules 4 and 13 were removed for PIE. The MCWO-calculated fast neutron fluences for Phase I to Phase-IV part 1B are presented in Ref. 6.

The Phase-IV part-2 MOX capsule arrangement was achieved by placing Capsules 6 and 12 in the two front middle positions, and Capsule 5 in the front top position as shown in Table 1 Capsule ID column. This report documents the MCWO-calculated cladding fast neutron fluences from Cycle 127C to the end of Cycle 132C (50 GWd/t) during Phase-IV part-2 MOX fuel irradiation.

## MCWO METHOD

In general, reactor physics analysis consists of multistep analysis methods. The multigroup diffusion equation with node-wise constant cross sections requires the fuel assembly to be appropriately homogenized. However, the complex spectral transitions in the WG-MOX fuel pellet present a serious challenge. The major source of uncertainty in the fuel burnup calculation comes from burnup-dependent cross-section (XS) and resonance treatment of neutron fluxes in the MOX fuel pellet. To avoid these problems, a validated depletion tool is used, which applies the Monte-Carlo code MCNP,<sup>7</sup> coupled with an isotope depletion code, ORIGEN-2<sup>8</sup>; this is the



MCWO<sup>1,9</sup> code. In the ATR test environment, the total fast neutron fluence in the cladding tube is the sum of the neutrons coming from the ATR core and fission neutrons from the MOX fuel pellets, which is a rather complicated process. MCWO was used to analyze the fission power density ratio and cumulative burnup of MOX fuel pellets versus irradiation effective full power days (EFPDs). MCWO can provide an accurate correction factor for the reactor parameters, such as capture-to-fission ratios, isotopic concentrations and compositions, fission power and neutron flux versus burnup.

## WG-MOX FUEL TESTING ASSEMBLY MODEL

MCNP can model extremely complex three-dimensional geometries. MCWO is quite accurate over a given region because MCNP-generated reaction rates are integrated over the continuous-energy nuclear data and the space within the region. Thus, any oddly or regularly shaped region in MCNP can usually be depleted. Applying this capability allows calculation of detailed nuclide concentration and power distributions within the MOX capsule as functions of burnup.

There are three MOX fuel test sections axially, with the center section at the core midplane, and three fuel capsules in each section, for a total of nine fuel capsules in the test assembly, which were all included in the ATR MCNP Core Model (ATRM) as shown in Figure 1.

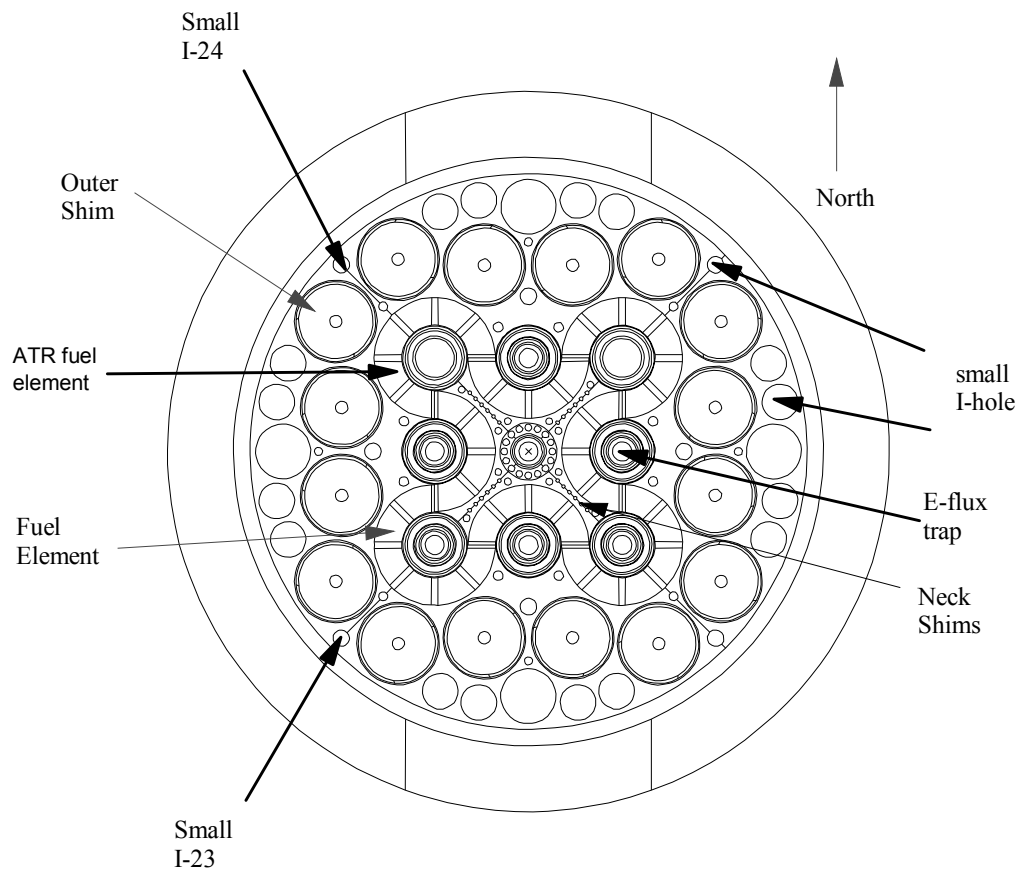


Figure 1. ATR MCNP core model cross-section view.

The WG-MOX test fuel pellet comprises five percent PuO<sub>2</sub> and 95% depleted UO<sub>2</sub>. Each fuel capsule is 0.415 cm in radius and 15.24 cm in length and contains 15 MOX fuel pellets. Channel 1 capsules are located away from the ATR core center, behind the capsules in channels 2 and 3. The validated MCWO method was used to perform the neutronics analysis of WG-MOX fuel in the ATR. The prediction of nuclide profiles and burnup distributions in irradiated MOX fuel pellets via this new methodology can provide valuable data for MOX fuel performance evaluation.

## RESULTS AND DISCUSSION

The experimental results of the Average Power Test (APT) include observations from the fuel fabrication process, PIE findings, U and Pu isotopic composition, and MOX fuel burnup.<sup>2,3,4,5</sup> All of the capsules were visually examined in the transfer canal at the ATR during the shuffling and transfer to ORNL for post-irradiation examination (PIE). The new refined MCNP model of the MOX fuel test assembly, with the Al thermal shield, located in the SW small I-23 hole for Cycles 127C was used to calculate the neutron flux (f4:n) tallies in the cladding tubes.

The weapons-grade mixed oxide (WG-MOX) fuel capsules were located in the small I-24 position during PHASE-I to PHASE-IV-1A. This report describes the results of the detailed MCNP Advanced Test Reactor (ATR) quarter core model physics analysis performed to provide the integrated fast neutron flux ( $E > 0.1$  MeV, and  $> 1.0$  MeV) at the end of PHASE-I, PHASE-II, PHASE-III, and PHASE-IV-1B of the MOX cladding Zr tubes.

The following flux normalization factor was used with the corresponding quadrant power (MW) to convert the MCNP tallies to the integrated fast neutron flux. Flux normalization factor = (fission neutron / fission) x (fission / MeV) x (MeV / quadrant core power MW-sec)

$$\begin{aligned} &= (2.43) \times (0.005) \times (6.25\text{E}+18 \text{ MeV/MW-sec}) \\ &= 7.5938 \times 10^{16} \text{ n/sec per quadrant MW.} \end{aligned}$$

### Phase-IV part-2 MCWO-Calculated Cladding Fast Neutron Fluence

Using the detailed ATR quarter core model calculated neutronic tallies, the MCWO-calculated Zr-cladding fast neutron fluence ( $E > 0.1$  MeV and  $E > 1.0$  MeV) distributions at the end of Phase-IV part-2 irradiation are tabulated in Tables 1 to 9.

MCWO-calculated fast neutron fluences at the end of the Cycle 127C irradiation are tabulated in Table 1. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.37$ ,  $1.28$ , and  $1.28 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 1. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 127C (50.3 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.31E+021	1.37E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.34E+021	1.28E+021
	Right 6	12	2.32E+021	1.28E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 128A irradiation are tabulated in Table 2. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.43$ ,  $1.35$ , and  $1.35 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 2. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 128A (59.8 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	$2.43\text{E}+021$	$1.43\text{E}+021$
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	$2.48\text{E}+021$	$1.35\text{E}+021$
	Right 6	12	$2.46\text{E}+021$	$1.35\text{E}+021$
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 129A irradiation are tabulated in Table 3. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.48$ ,  $1.41$ , and  $1.41 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 3. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 129A (51.7 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.53E+021	1.48E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.60E+021	1.41E+021
	Right 6	12	2.58E+021	1.41E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 129B irradiation are tabulated in Table 4. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.52$ ,  $1.45$ , and  $1.46 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 4. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 129B (43.8 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.61E+021	1.52E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.70E+021	1.45E+021
	Right 6	12	2.68E+021	1.46E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 130A irradiation are tabulated in Table 5. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.52$ ,  $1.45$ , and  $1.46 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 5. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 130A (51.5 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.71E+021	1.56E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.80E+021	1.50E+021
	Right 6	12	2.79E+021	1.51E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 130B irradiation are tabulated in Table 6. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.60$ ,  $1.55$ , and  $1.55 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 6. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 130B (44.5 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.78E+021	1.60E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.89E+021	1.55E+021
	Right 6	12	2.88E+021	1.55E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		



MCWO-calculated fast neutron fluences at the end of the Cycle 131A irradiation are tabulated in Table 7. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.64$ ,  $1.59$ , and  $1.60 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 7. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 131A (48.5 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.87E+021	1.64E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	2.99E+021	1.59E+021
	Right 6	12	2.98E+021	1.60E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 132A irradiation are tabulated in Table 8. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.67$ ,  $1.64$ , and  $1.64 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 8. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 132A (44.1 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	2.94E+021	1.67E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	3.08E+021	1.64E+021
	Right 6	12	3.06E+021	1.64E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

MCWO-calculated fast neutron fluences at the end of the Cycle 132C irradiation (50 GWd/t) are tabulated in Table 9. The Zr-cladding fast neutron fluences ( $E > 1.0$  MeV) of the removed MOX capsules 5, 6 and 12 reached  $1.71$ ,  $1.68$ , and  $1.58 \times 10^{21}$  n/cm<sup>2</sup>, respectively.

Table 9. The integrated fast neutron flux ( $E > 0.1$  MeV and  $E > 1.0$  MeV) of MOX fuel pin's Zr-cladding at the end of Cycle 132C (50.3 EFPDs) irradiation.

Target location		Capsule ID <sup>a</sup>	Fast neutron fluence ( $E > 0.1$ MeV)	Fast neutron fluence ( $E > 1.0$ MeV)
			N/cm <sup>2</sup>	
Top Zr-cladding	Back 1	SST		
	Left 2	5	3.03E+021	1.71E+021
	Right 3	SST		
Middle Zr-cladding	Back 4	SST		
	Left 5	6	3.18E+021	1.68E+021
	Right 6	12	3.16E+021	1.68E+021
Bottom	Back 7	SST		
	Left 8	SST		
	Right 9	SST		

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